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EFFECTS OF LINEAR VELOCITIES CAUSED BY GUN PLATFORM MOTION ON GUN FIRING ACCURACY

BY WINSTON C. CHOW

WEAPONS SYSTEMS DEPARTMENT

SEPTEMBER 1984

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Linear velocities imparted to a projectile fired from a moving platform influence the probability of hitting (Ph) a target. These velocities are not usually adjusted by the gun stabilization system. At 2000m, it is shown for a typical platform motion that the Ph for a 25mm gun shooting at a 2.29 x 2.29m^2 target is lowered from .453 to .348. A method of modeling these aiming errors if uncompensated by the fire control system is discussed.

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FOREWORD

This report explains how velocities and projectiles from guns mounted on a moving vehicle are affected by linear velocities of the vehicle. A method of modeling aiming errors caused by such linear velocities, if uncompensated by the fire control systems, is explained.

This work was done in support of accuracy model efforts on the proposed LVT(X) amphibian vehicle and the Joint Munitions Effectiveness Manual Surface-to-Surface Burst Fire Accuracy Program.

This report was reviewed and approved by R. G. Hinkle; G. E. Hornbaker, Head, Systems Accuracy Branch; and D. S. Malyevac, Head, Systems Analysis Division.

Approved by:

R. J. ARTHUR, Deputy Head
Weapons Systems Department

CONTENTS

INTRODUCTION

Along with the mean velocity that takes a land or water vehicle from one place to another, there are six types of oscillatory motions, which are rotational–roll, pitch, and yaw; and translational–surge, sway, and heave. These six types of motion, as well as the mean vehicle velocity, cause linear velocities that add to the muzzle velocities of projectiles fired from guns located on a moving vehicle.

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The stabilization system of a gun can compensate for part or all of the angular deviations of the aimpoint caused by roll, pitch, and yaw. However, the linear velocities imparted by these rotations as well as the translations are not accounted for by the stable element. Moreover, there are some fire control systems in use that do not account for the same, and so in these systems, the unaccounted velocities affect gun fire accuracy. This report provides a method to model the errors caused by these linear velocities, if uncompensated by the fire control. Given some assumptions, the formulas derived are exact with absolutely no approximations, and they can be utilized by writing a computer program.

This work was necessary since the operational requirements of the LVT(X) amphibian vehicle included the firing of its weapon from water near the shore. Also, the Joint Munitions Effectiveness Manual (JMEM) Surface-to-Surface Delivery Accuracy Working Group needed a method to model gun fire errors due to firing from a moving platform.

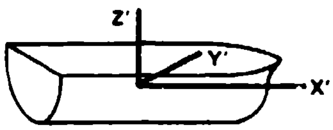
METHODOLOGY

In order to derive the model, equations that calculate the linear velocity in the (North, West, up) frame due to rotational motion are explained. Transformations are performed on all other motions of the vehicle and muzzle velocities to express them in the above frame. The velocities are then added to the muzzle velocity, and the azimuth and elevation formulas for the new velocity are derived from the sum. The errors are calculated by comparing the new azimuth and elevation with the initial ones from muzzle velocity. A computer program using the methodology of this report is given in Appendix A.

LINEAR VELOCITY DUE TO ROTATIONAL MOTION

It is assumed that the gun barrel is pivoted on the trunnion. The stabilization system can adjust the gun barrel to compensate for angular deviations caused by vehicle rotational oscillations, but it cannot adjust for the linear velocities. Since the pivot of the gun barrel is assumed to be at the trunnion, the linear velocity imparted on the projectile from vehicle motion is equal to the linear velocity on the trunnion. This is because the gun barrel and muzzle do not rotate with the vehicle (due to the stable element) while the trunnion does. A small additional velocity imparted while the projectile travels down the gun barrel will be discussed in Appendix B.

Assuming that the centers of rotation of roll, pitch, and yaw coincide, define X′ pointing towards the fore, Z′ pointing up, and Y′ pointing in the direction that forms a right-handed system. Also, X′ is in the centerline of the vehicle, and the point (0,0,0) is in the center of rotation.



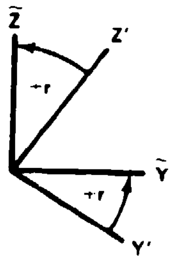
An equation will now be derived for the linear velocity with respect to a (North, West, up) frame imparted by the rotational motion.

Let r = roll, p = pitch, h = heading; assuming the angle of the mean vehicle velocity vector is constant,

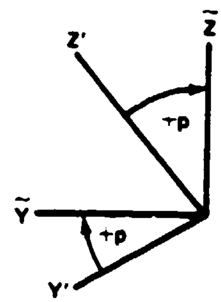
$$\frac{dh}{dt} = \left(\frac{d\ YAW}{dt}\right) \tag{1}$$

Also, let A = roll, B = pitch, C = heading coordinate rotations. The positive direction of roll and heading are opposite of the conventions in a right-handed system. The ∿s in the following frames show that the axis is not in the (North West, up) frame.

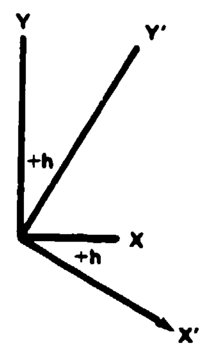
$$A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos r & \sin r \\ 0 & -\sin r & \cos r \end{pmatrix} \text{ roll}$$



$$B = \begin{pmatrix} \cos p & 0 & \sin p \\ 0 & 1 & 0 \\ -\sin p & 0 & \cos p \end{pmatrix} \quad \text{pitch}$$



$$C = \begin{pmatrix} \cos h & \sin h & 0 \\ -\sin h & \cos h & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{heading}$$



Multiply CBA by the position vector (R') of the trunnion in the primed (platform) frame gives its position vector in the (X, Y, Z) = (North, West, up) = (N,W,U) frame, which is assumed to be fixed (Equation (2)). Hence,

$$\begin{pmatrix} R_x \\ R_y \\ R_z \end{pmatrix} = C\ B\ A \begin{pmatrix} R'_x \\ R'_y \\ R'_z \end{pmatrix} \quad \text{i.e., } \mathbf{R} = CBA\mathbf{R}' \tag{2}$$

where R'_x is the roll, R'_y is the pitch, and R'_z is the heading and yaw axes.

The linear velocity with respect to (X,Y,Z) is simply the derivative of R = R(t) as shown in Equation (3).

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} \frac{dR_x}{dt} \\ \frac{dR_y}{dt} \\ \frac{dR_z}{dt} \end{pmatrix} = \frac{d}{dt}\left[C\ B\ A \begin{pmatrix} R'_x \\ R'_y \\ R'_z \end{pmatrix} \right] \tag{3}$$

In order to calculate the derivative on the right-hand side of Equation (3), the following definition must be made by Equation (4). Given matrix

$$M = (M_{ij}) \tag{4}$$

Equation (5) is the definition of the derivative of a matrix, which is the derivative of every element in the matrix.

$$\frac{dM}{dt} = \left(\frac{dM_{ij}}{dt}\right) \tag{5}$$

Equation (6) is a mathematical theorem. Given matrices A_1, A_2, ... A_n and vector $\mathbf{R}$

$$\frac{d}{dt} \prod_{i=1}^{n} A_i\ \mathbf{R} = \sum_{i=1}^{n} (A_1 \ldots \frac{dA_i}{dt} \ldots A_n \mathbf{R}) + \prod_{i=1}^{n} A_i \frac{d\mathbf{R}}{dt} \tag{6}$$

The proof is given in Appendix C.

From Equations (4) and (5), (V_x, V_y, V_z) can be calculated as follows.

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \frac{dC}{dt} BA\mathbf{R}' + C\frac{dB}{dt} A\mathbf{R}' + CB\frac{dA}{dt} \mathbf{R}' + C\ B\ A\frac{d\mathbf{R}'}{dt} \tag{7}$$

Note that the last term on the right is zero, since $\mathbf{R}'$ is assumed fixed on the vehicle coordinate system. Hence,

$$V_{rot} = \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \frac{dC}{dt}BA\mathbf{R}' + C\frac{dB}{dt}A\mathbf{R}' + CB\frac{dA}{dt}\mathbf{R}' \tag{8}$$

where

V_{rot} represents the linear velocity imparted by rotational motion.

The matrix derivatives shown are obtained by differentiating each element of the original matrices.

$$\frac{dA}{dt} = \frac{d}{dt}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos r & \sin r \\ 0 & -\sin r & \cos r \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\sin r\,\frac{dr}{dt} & \cos r\,\frac{dr}{dt} \\ 0 & -\cos r\,\frac{dr}{dt} & -\sin r\,\frac{dr}{dt} \end{pmatrix}$$

$$\frac{dB}{dt} = \begin{pmatrix} -\sin p\,\frac{dp}{dt} & 0 & \cos p\,\frac{dp}{dt} \\ 0 & 0 & 0 \\ -\cos p\,\frac{dp}{dt} & 0 & -\sin p\,\frac{dp}{dt} \end{pmatrix}; \quad \frac{dC}{dt} = \begin{pmatrix} -\sin(h)\,\frac{dh}{dt} & \cos(h)\,\frac{dh}{dt} & 0 \\ -\cos(h)\,\frac{dh}{dt} & -\sin(h)\,\frac{dh}{dt} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

An alternate equation can be derived to calculate the linear velocity due to rotational motion by noting that

$$V_{rot} = \frac{d\mathbf{R}}{dt} = \mathbf{W} \times \mathbf{R} \tag{9}$$

where **R** and **W** are both expressed with respect to a fixed frame that is assumed to be (N,W,U). From previous explanations, it is known that

$$\mathbf{R} = \begin{pmatrix} R_x \\ R_y \\ R_z \end{pmatrix} = CBA\mathbf{R}' \tag{10}$$

where **R'** is the same as the one that was already defined. **W** must be found, which is the rotation with respect to the fixed frame. Roll, pitch, and heading are given. Only heading, whose negative direction is up, can be considered in the fixed frame. The roll axis can be transformed into the fixed frame via rotations with magnitudes equal to pitch and heading, respectively, but in opposite directions. The pitch axis is parallel to the earth's horizontal axes and at an angle of the heading's magnitude clockwise from the West. Hence, the pitch axis can be transformed to the fixed frame by a rotation of magnitude equal to heading but in the opposite direction. Hence,

$$\mathbf{W} = CB \begin{pmatrix} \frac{dr}{dt} \\ 0 \\ 0 \end{pmatrix} + C \begin{pmatrix} 0 \\ \frac{dp}{dt} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{dh}{dt} \end{pmatrix} \tag{11}$$

LINEAR VELOCITY DUE TO TRANSLATIONAL MOTION

In order to describe the linear velocity caused by surge, sway, and heave, a precise mathematical definition of these motions must be made. Since there seems to be some ambiguity on an accepted definition, they are defined in the next paragraph.

The surge, sway, and heave are oscillatory translational motions defined on a coordinate system whose origin is the mean location of the center of rotation that is assumed to be at or very near the mean location of the center of mass. The X-axis is the surge axis and points toward the direction of the mean velocity vector, if the vehicle is moving forward; and negative of this vector, if the vehicle is going backwards. The Z-axis is the heave axis and is pointed up with respect to the earth. The sway axis is horizontal and points in a direction that completes a right-handed system. As above, assume the vehicle mean velocity vector is constant. If the vehicle is not traveling, such as a ship floating in water, the X-axis is defined as the mean location of the centerline of the vehicle.

Given the translational oscillations in the above coordinate system, these motions can be expressed in the (N,W,U) frame by the following transformation:

$$V_{osc\ transl} = \begin{pmatrix} V_n \\ V_w \\ V_u \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} V_x' \\ V_y' \\ V_z' \end{pmatrix} \tag{12}$$

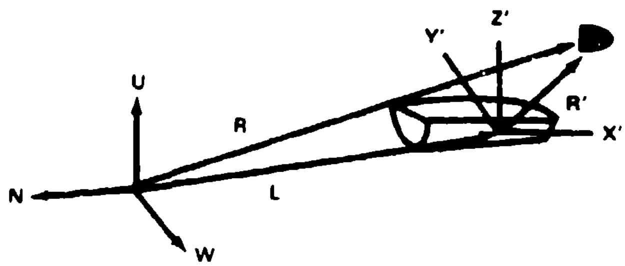
where ϕ is the vehicle mean velocity angle from the North. As before, let positive ϕ be the opposite of the convention, that is, ϕ is defined as clockwise if $\phi > 0$.

The remaining translational motion is the mean vehicle velocity itself, and it is not oscillatory. Given the mean speed and ϕ as defined above, this velocity in the (N,W,U) frame is as follows:

$$V_{mean\ vel} = |V_{mean\ vel}| \; (\cos\phi, \; -\sin\phi, \; 0) \qquad (13)$$

ACTUAL PROJECTILE VELOCITY

The actual projectile velocity is the vector sum of the given velocity, which is the muzzle velocity V_{muzzle} plus all of the above linear velocities imparted to the projectile by vehicle motion at $t = t_o$ when the gun is fired. In the (N,W,U) frame



(X', Y', Z') = VEHICLE FRAME

$$V_{muzzle} = |V_{muzzle}| \left(\cos(El_o)\cos(A_{z_o}^*),\ -\cos(El_o)\sin(A_{z_o}^*),\ V\sin(El_o)\right) \tag{14}$$

where

El_o = initial gun elevation

$A_{z_o}^*$ = Az(initial) + Heading

A_z (initial) = gun bearing with respect to forward of the platform

Adding all the various velocities at $t = t_o$, the actual bullet velocity V_b is as follows:

$$\begin{aligned} V_b &= V_{muzzle} + \left[V_{vehicle}\right]_{t = t_o} \\ &= V_{muzzle} + \left[V_{rot} + V_{osc\ transl} + V_{mean\ vel}\right]_{t = t_o} \end{aligned} \tag{15}$$

where b denotes bullet. $V_{mean\ vel}$ is often assumed to be compensated after the first round, and so it may need to be removed in a computer model after the first round.

The correspondence of the terms of Equation (15) to that derived from Coriolis' of classical mechanics at t_o further demonstrates the truth of the former. Let $\mathbf{R}$ be the t_o bullet position in (N,W,U). Let $\mathbf{R}'$ be the t_o bullet position in the vehicle frame assuming for now $\mathbf{R}'$ = trunnion position at t_o and $\mathbf{L}$ be the vehicle frame's position in (N,W,U).

$$\frac{d\mathbf{R}}{dt} = \frac{d\mathbf{R}'}{dt} + \frac{d\mathbf{L}}{dt} \tag{16}$$

From Coriolis' equations in two forms,

$$\frac{d\mathbf{R}'}{dt} = \frac{d'\mathbf{R}'}{dt} + W \times \mathbf{R}' \tag{17}$$

$$\frac{d\mathbf{R}'}{dt} = M\frac{d'\mathbf{R}'_v}{dt} + \frac{dM}{dt}\mathbf{R}'_v \tag{18}$$

where $\frac{d}{dt}$ and $\frac{d'}{dt}$ are derivatives in the (N,W,U) and (X', Y', Z') frames, respectively, M = rotation matrix from (X', Y', Z') to (N,W,U) and $\mathbf{R}'_v$ is $\mathbf{R}'$ in terms of (X', Y', Z'). Hence,

$$\frac{d\mathbf{R}}{dt} = \frac{d'\mathbf{R}'}{dt} + \mathbf{W} \times \mathbf{R}' + \frac{d\mathbf{L}}{dt} \text{ and also} \tag{19}$$

$$\frac{d\mathbf{R}}{dt} = M\ \frac{d'\mathbf{R}'_v}{dt} + \frac{dM}{dt}\mathbf{R}'_v + \frac{d\mathbf{L}}{dt} \tag{20}$$

Letting $\mathbf{R}'$ be in terms of (N,W,U), $\frac{d'\mathbf{R}'}{dt}$ of Equation (19) and M $\frac{d'\mathbf{R}'_v}{dt}$ of Equation (20) both equal V_{muzzle} with respect to (X', Y', Z') at t_o but in terms of (N,W,U).

$W \times \mathbf{R}' = W$x (trunnion position) and

$$\frac{dM}{dt}\ \mathbf{R}'_v = \frac{dM}{dt} \times (\text{trunnion position})_v$$

both give V_{rot} at t_o with respect to and in terms of (N,W,U). Note that M is C B A and

$$\frac{dM}{dt} = \dot{C}BA + C\dot{B}A + CB\dot{A} \text{ as before;}$$

$$\frac{d\mathbf{L}}{dt} = V_{mean\ vel} + V_{oscil\ trans} \text{ and}$$

$$\frac{d\mathbf{R}}{dt} = V_b$$

Hence, Equations (19) and (20) contain exactly the terms on the right side of Equation (15) at t_o.

Since the gun is pivoted on the trunnion, the above holds even if $\mathbf{R}' \neq$ trunnion position at t_o. In this case, one adds a fixed translation to (X', Y', Z') so that the new origin is the center of rotation of the bullet's initial position. The vector from this new location to the bullet position is still $\mathbf{R}'$ or $\mathbf{R}'_v$ and so all terms containing $\mathbf{R}'$ or $\mathbf{R}'_v$ are unchanged. Letting

$\hat{\mathbf{L}}$ = new $\mathbf{L}$, $\hat{\mathbf{L}} = \mathbf{L}$ + fixed translation implies that

$$\frac{d\hat{\mathbf{L}}}{dt} = \frac{d\mathbf{L}}{dt}$$

Letting $\hat{\mathbf{R}}$ = new $\mathbf{R}$, $\hat{\mathbf{R}} = \hat{\mathbf{L}} + \mathbf{R}'$ since $\mathbf{R} = \mathbf{L} + \mathbf{R}'$, and so

$$\frac{d\hat{\mathbf{R}}}{dt} = \frac{d\hat{\mathbf{L}}}{dt} + \frac{d\mathbf{R}'}{dt} = \frac{d\mathbf{L}}{dt} + \frac{d\mathbf{R}'}{dt} = \frac{d\mathbf{R}}{dt} \tag{21}$$

Therefore, assuming $\mathbf{R}' \neq$ trunnion position at t_o changes nothing.

CALCULATION OF ERRORS

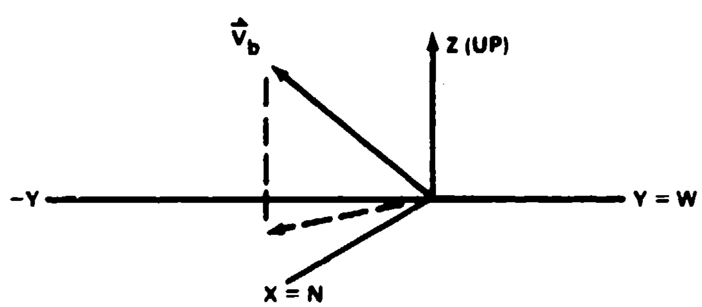
$$El_{new} = \sin^{-1} \frac{V_{z_b}}{V_b} \tag{22}$$

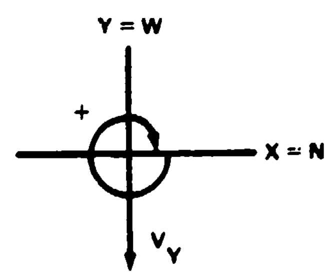
$$AZ^*_{new} = \cos^{-1} \frac{V_{x_b}}{\sqrt{V^2_{x_b} + V^2_{y_b}}} \qquad \text{if } V_y < 0 \tag{23}$$

$$AZ^*_{new} = -\cos^{-1} \frac{V_{x_b}}{\sqrt{V^2_{x_b} + V^2_{y_b}}} \tag{24}$$

if $V_y > 0$, since clockwise is defined positive in this application.

See the following diagram.





$$AZ^*_{new} = AZ_{new} + \text{Heading} \tag{25}$$

The azimuth and elevation errors are as follows:

$$\epsilon_{AZ} = AZ^* - AZ^*_0 \tag{26}$$

$$\epsilon_{El} = El_{new} - El_o \qquad (27)$$

The distance errors for a flat trajectory are as follows:

$$\epsilon'_{AZ} = (\text{RANGE})\ (\epsilon_{AZ}) \qquad (28)$$

$$\epsilon'_{El} = (\text{RANGE})\ (\epsilon_{El}) \qquad (29)$$

Hence, we have modeled the gun shot errors caused by linear velocities imparted by vehicle motion. If one desires a more precise assumption than a flat trajectory, other formulas not given here can be used to find $(\epsilon'_{AZ}, \epsilon'_{El})$ when $(\epsilon_{AZ}, \epsilon_{El})$ as calculated above is given.

MODELS OF VEHICLE MOTION

A time series model of vehicle motion in water or land can be obtained experimentally. The following is a simple analytical model of vehicle motion in water, which is implemented in the model and may be useful in some applications.

$$r = \text{roll} = MAX_r \sin\left(\frac{2\pi}{T_r} t\right) \qquad (30)$$

$$p = \text{pitch} = MAX_p \sin\left(\frac{2\pi}{T_p} t\right) \qquad (31)$$

$$h = \text{heading} = MAX_{Yaw} \sin\left(\frac{2\pi}{T_y} t\right) + \phi \qquad (32)$$

where T_is are periods and MAX_is are maximum amplitudes, ϕ = angle of ship velocity vector (assumed constant), and t = time.

$$\dot{r} = \frac{2\pi}{T_r} MAX_r \cos\left(\frac{2\pi}{T_r} t\right) \qquad (33)$$

$$\dot{p} = \frac{2\pi}{T_p} \; MAX_p \; \cos\left(\frac{2\pi}{T_p}\, t\right) \tag{34}$$

$$\dot{h} = \frac{2\pi}{T_y} \; MAX_{Yaw} \; \cos\left(\frac{2\pi}{T_y}\, t\right) \tag{35}$$

For surge, sway, and heave, only their derivatives are used, that is, their velocities. So,

$$V_{surge} = \frac{2\pi}{T_x} \; MAX\ (SURGE) \; \cos\left(\frac{2\pi}{T_x}\, t\right) \tag{36}$$

$$V_{sway} = \frac{2\pi}{T_y} \; MAX\ (SWAY) \; \cos\left(\frac{2\pi}{T_y}\, t\right) \tag{37}$$

$$V_{heave} = \frac{2\pi}{T_z} \; MAX\ (HEAVE) \; \cos\left(\frac{2\pi}{T_z}\, t\right) \tag{38}$$

where T_is are the periods and t = time.

IMPLEMENTATION OF THE MODEL

A computer program, AIMPT, was written in FORTRAN that gives the aimpoint error (azimuth and elevation) due to linear velocities, where the linear velocity imparted by rotational motion was modeled by the matrices method. Also, platform motion itself was simulated in a program called SHIP that uses a sinusoidal model. A program called HITPROB, written by the U.S. Army Materiel Systems Analysis Activity* was used as a driver to the linear velocity model. This program simulates the probability of hitting a square or rectangular target by projectiles fired from a 25mm chain gun mounted on a Bradley Fighting Vehicle. Listings of AIMPT and SHIP are given below, and the program was run one time without linear velocities and one time with linear velocities. The listing of the program is in Appendix A.

*Larry Bowman, A *Methodology for Estimating Quasicombat Dispersions for Automatic Weapons*, Interim Note G-103, U.S. Army Material Systems Analysis Activity, Aberdeen Proving Ground, Maryland, April 1982.

Input parameters to AIMPT and SHIP were as follows:

Gun position	20° AZ 20° El
Bullet muzzle velocity	1345 m/sec
Bearing at vehicle from north	60°
Maximum roll	0.0873 rad
Maximum pitch	0.0873 rad
Maximum yaw	0.0349 rad

Trunnion location from center of rotation (1., 1.73205, 1.73205) in m (meters)

Roll period	2 sec	Maximum sway amplitude	0.1 m
Pitch period	2 sec	Maximum heave amplitue	0.5 m
Yaw period	5 sec	Surge period	10 sec
Vehicle forward speed	4 m/sec	Sway period	10 sec
Maximum surge amplitude	0.1 m	Heave period	2 sec
		Time increment	0.6 sec

The output is as follows

Range	2000 m
Target size	2.286 x 2.286 m^2
Hit probability without linear velocities	0.453
Hit probability with linear velocities	0.348

As seen, the probability of hit has been noticeably lowered by the presence of linear velocities.

CONCLUSION

The model explained in this report and implemented by the computer program described shows that linear velocities, imparted by gun platform motion on projectiles, influence the probability of hitting a target.

RECOMMENDATION

In modeling gun fire accuracy, consideration should be given to the effects of linear velocities, imparted by platform motion, on accuracy. A model such as the one described in this report or actual test data can be used to model this effect.

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APPENDIX A

COMPUTER PROGRAM

```
      SUBROUTINE AIMPT(KVEL)
C KVEL DETERMINES WHETHER TO ACC'T FOR SHIP VEL.KVEL=0 MEANS YES
      IMPLICIT REAL*8 (A-H,O-Z)
C AZOD,ELOD=GUN AZ & ELEV RESP IN DEG.VEL=PROJ SPEED.VELDEG=SHIP VEL
C ANGLE FROM NORTH.BDROLL,BDPIT,BDYAW=MAX ROLL,PITCH,YAW RESP.TRUN=
C TRUNNION POS.TR,TP,TY=PERIOD OF ROLL,PITCH,YAW RESP.VSHIP=SHIP SPEED
      COMMON /SHIP1/TRUN(3),VELDEG,VEL,ELOD,AZOD,YAW,ROLL,PITCH,WROLL,
     &WPITCH,WHEAD,DVR(3),AZERR,ELERR,RANGE,HEADO,PI
      COMMON/SHIP2/VSUR,VSWA,VHEA,DVT(3),DVS(3),VSHIP,BDROLL,BDPIT,
     &BDYAW,TR,TP,TY,TSUR,TSWA,THEA,DT,BDSUR,BDSWA,BDHEA
C COMMON.SHIP2.GIVES MAX SURGE,SWAY,HEAVE;THEIR PERIODS;SHIP SPEED RESP.
      DIMENSION A(3,3),B(3,3),C(3,3),ADOT(3,3),BDOT(3,3),CDOT(3,3)
      DIMENSION TRANS1(3),TRANS2(3)
      DIMENSION V1(3),V2(3),V3(3)
C VELDEG=ANGLE OF SHIP VEL VECTOR FROM NORTH;VEL=VEL(MAG) OF BULLET;
C DVR(3)=LINEAR VEL FROM ROLL,PITCH, AND YAW.
      RADFAC=PI/180.
      DEGFAC=180./PI
      VELRAD=RADFAC*VELDEG
C HEAD=HEADING=SHIP VEL VEC ANGLE+YAW
      HEAD=VELRAD+YAW
C GET VEL VECTOR OF BULLET;AZZ=HEADING AT TO PLUS AZ(FROM SHIP CTRLINE)
C AZOD,ELOD ARE EL AND AZ OF BULLET AT TIME TO.
C HEADO=HEADING AT TIME TO
      AZO=RADFAC*AZOD
      ELO=RADFAC*ELOD
      AZZ=AZO+HEADO
      VX=VEL*COS(ELO)*COS(AZZ)
      VY=-VEL*COS(ELO)*SIN(AZZ)
      VZ=VEL*SIN(ELO)
C GET VEL VECTOR FROM ROLL, PITCH, AND HEADING
      DO 5 I=1,3
      DO 6 J=1,3
      A(I,J)=0.
      B(I,J)=0.
      C(I,J)=0.
      ADOT(I,J)=0.
      BDOT(I,J)=0.
      CDOT(I,J)=0.
    6 CONTINUE
    5 CONTINUE
      A(1,1)=1.0
      A(2,2)=COS(ROLL)
      A(2,3)=SIN(ROLL)
      A(3,2)=-SIN(ROLL)
      A(3,3)=COS(ROLL)
      B(1,1)=COS(PITCH)
      B(1,3)=SIN(PITCH)
      B(3,1)=-SIN(PITCH)
      B(3,3)=COS(PITCH)
      B(2,2)=1.0
      C(1,1)=COS(HEAD)
      C(2,1)=-SIN(HEAD)
      C(1,2)=SIN(HEAD)
      C(2,2)=COS(HEAD)
      C(3,3)=1.0
      ADOT(2,2)=-SIN(ROLL)*WROLL
```

```
      ADOT(2,2)=COS(ROLL)*WROLL
      ADOT(3,2)=-COS(ROLL)*WROLL
      ADOT(3,3)=-SIN(ROLL)*WROLL
      BDOT(1,1)=-SIN(PITCH)*WPITCH
      BDOT(1,3)=COS(PITCH)*WPITCH
      BDOT(3,1)=-COS(PITCH)*WPITCH
      BDOT(3,3)=-SIN(PITCH)*WPITCH
      CDOT(1,1)=-SIN(HEAD)*WHEAD
      CDOT(1,2)=COS(HEAD)*WHEAD
      CDOT(2,1)=-COS(HEAD)*WHEAD
      CDOT(2,2)=-SIN(HEAD)*WHEAD
      CALL MATPRO(A,TRUN,TRANS1,3,3,1)
      CALL MATPRO(B,TRANS1,TRANS2,3,3,1)
      CALL MATPRO(CDOT,TRANS2,V1,3,3,1)
      CALL MATPRO(A,TRUN,TRANS1,3,3,1)
      CALL MATPRO(BDOT,TRANS1,TRANS2,3,3,1)
      CALL MATPRO(C,TRANS2,V2,3,3,1)
      CALL MATPRO(ADOT,TRUN,TRANS1,3,3,1)
      CALL MATPRO(B,TRANS1,TRANS2,3,3,1)
      CALL MATPRO(C,TRANS2,V3,3,3,1)
      CALL MATSUM(V1,V2,TRANS1,3,1)
C DVR IS THE LINEAR VEL CAUSED BY ROLL,PITCH, & YAW.
      CALL MATSUM(TRANS1,V3,DVR,3,1)
C CALCULATE TRANSLATION VEL.
      DVT(1)=VSUR*COS(VELRAD)+VSWA*SIN(VELRAD)
      DVT(2)=-VSUR*SIN(VELRAD)+VSWA*COS(VELRAD)
      DVT(3)=VHEA
      DVS(1)=0.
      DVS(2)=0.
      IF(KVEL.EQ.0)DVS(1)=VSHIP*COS(VELRAD)
      IF(KVEL.EQ.0)DVS(2)=-VSHIP*SIN(VELRAD)
      DVS(3)=0.
C DVT IS THE LIN VEL FROM HEAVE,SURGE, & SWAY; DVS=SHIP LIN VEL.
C CALC. NEW V OF PROJECTILE.
      VXNEW=VX+DVR(1)+DVT(1)+DVS(1)
      VYNEW=VY+DVR(2)+DVT(2)+DVS(2)
      VZNEW=VZ+DVR(3)+DVT(3)+DVS(3)
C CALC. NEW EL AND AZ IN DEGREES.
      VXYNEW=SQRT(VXNEW**2.+VYNEW**2.)
      VNEW=SQRT(VXNEW**2.+VYNEW**2.+VZNEW**2.)
      ELNEW=ASIN(VZNEW/VNEW)
      AZSTAR=ACOS(VXNEW/VXYNEW)
      AZSTAR=DEGFAC*AZSTAR
      ELNEW=DEGFAC*ELNEW
      IF(VYNEW.GT.0.)AZSTAR=-AZSTAR
      AZDIFF=AZSTAR-(AZZ*DEGFAC)
      AZZZ=AZZ*DEGFAC
      ELDIFF=ELNEW-ELOD
      AZERR=RANGE*RADFAC*AZDIFF
      ELERR=RANGE*RADFAC*ELDIFF
C     WRITE(6,*)'AZDIFF,ELDIFF',AZDIFF,ELDIFF
      RETURN
      END
```

```
      SUBROUTINE SHIP(T)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/SHIP1/TRUN(3),VELDEG,VEL,ELOD,AZOD,YAW,ROLL,PITCH,WROLL,
     &WPITCH,WHEAD,DVR(3),AIERR,ELERR,RANGE,HEADO,PI
      COMMON/SHIP2/VSUR,VSWA,VHEA,DVT(3),DVS(3),VSHIP,BDROLL,BDPIT,
     &BDYAW,TR,TP,TY,TSUR,TSWA,THEA,DT,BDSUR,BDSWA,BDHEA
      ARGROL=2.*PI/TR
      ARGPIT=2.*PI/TP
      ARGYAW=2.*PI/TY
C OBTAINS SHIP ANGULAR POSITION
      ROLL=BDROLL*SIN(ARGROL*T)
      PITCH=BDPIT*SIN(ARGPIT*T)
      YAW=BDYAW*SIN(ARGYAW*T)
C OBTAINS SHIP ANGULAR VELOCITY
      WROLL=BDROLL*ARGROL*COS(ARGROL*T)
      WPITCH=BDPIT*ARGPIT*COS(ARGPIT*T)
      WHEAD=BDYAW*ARGYAW*COS(ARGYAW*T)
C OBTAINS  SHIP TRANSLATIONAL VELOCITY
      ARGSUR=2.*PI/TSUR
      ARGSWA=2.*PI/TSWA
      ARGHEA=2.*PI/THEA
      VSUR=BDSUR*ARGSUR*COS(ARGSUR*T)
      VSWA=BDSWA*ARGSWA*COS(ARGSWA*T)
      VHEA=BDHEA*ARGHEA*COS(ARGHEA*T)
      RETURN
      END
```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 $CODE	244	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 $LOCAL	72	PIC CON REL LCL NOSHR NOEXE RD WRT QUAD
3 SHIP1	168	PIC OVR REL GBL SHR NOEXE RD WRT LONG
4 SHIP2	184	PIC OVR REL GBL SHR NOEXE RD WRT LONG
Total Space Allocated	668	

ENTRY POINTS

Address	Type	Name
0-00000000		SHIP

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name	Address	Type	Name
2-00000028	R*8	ARGHEA	2-00000008	R*8	ARGPIT	2-00000000	R*8	ARGROL	2-00000018	R*8	ARGSUR
2-00000020	R*8	ARGSWA	2-00000010	R*8	ARGYAW	3-00000030	R*8	AZOD	3-00000080	R*8	AZERR
4-000000B0	R*8	BDHEA	4-00000058	R*8	BDPIT	4-00000050	R*8	BDROLL	4-000000A0	R*8	BDSUR
4-000000A8	R*8	BDSWA	4-00000060	R*8	BDYAW	4-00000098	R*8	DT	3-00000028	R*8	ELOD

```
          SUBROUTINE MATPRO(A,B,C,IROWA,ICOLA,ICOLB)
          IMPLICIT REAL*8 (A-H,O-Z)
C GIVES MATRIX PRODUCT
          DIMENSION A(IROWA,ICOLA),B(ICOLA,ICOLB),C(IROWA,ICOLB)
          DO 10 I=1,IROWA
          DO 20 K=1,ICOLB
          C(I,K)=0
          DO 30 J=1,ICOLA
          C(I,K)=C(I,K)+A(I,J)*B(J,K)
       30 CONTINUE
       20 CONTINUE
       10 CONTINUE
          RETURN
          END
```

PROGRAM SECTIONS

Name	Bytes	Attributes
0 $CODE	210	PIC CON REL LCL SHR EXE RD NOWRT LONG
2 $LOCAL	176	PIC CON REL LCL NOSHR NOEXE RD WRT LONG
Total Space Allocated	386	

ENTRY POINTS

Address	Type	Name
0-00000000		MATPRO

VARIABLES

Address	Type	Name	Address	Type	Name	Address	Type	Name	Address	Type	Name
2-00000000	I*4	I	AP-00000014@	I*4	ICOLA	AP-00000018@	I*4	ICOLB	AP-00000010@	I*4	IROWA
2-00000008	I*4	J	2-00000004	I*4	K						

ARRAYS

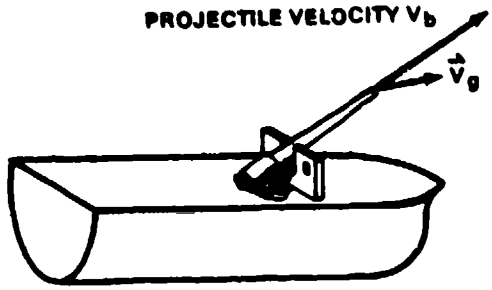
Address	Type	Name	Bytes	Dimensions
AP-00000004@	R*8	A	**	(*, *)
AP-00000008@	R*8	B	**	(*, *)
AP-0000000C@	R*8	C	**	(*, *)

```
                                                    25-Jul-1984 08:39:35    VAX-11 FORTRAN V3.5-62                Page 24
                                                    24-Jul-1984 15:56:40    SYS$SYSDEVICE:[CHOW.HITPROB]PH2SMM.FOR;5

          SUBROUTINE MATSUM(A,B,C,IROWA,ICOLA)
          IMPLICIT REAL*8 (A-H,O-Z)
    C GIVES MATRIX SUM
          DIMENSION A(IROWA,ICOLA),B(IROWA,ICOLA),C(IROWA,ICOLA)
          DO 10 I=1,IROWA
          DO 20 J=1,ICOLA
          C(I,J)=A(I,J)+B(I,J)
       20 CONTINUE
       10 CONTINUE
          RETURN
          END


PROGRAM SECTIONS

    Name                                Bytes   Attributes

  0 $CODE                                 177   PIC CON REL LCL   SHR   EXE   RD NOWRT LONG
  2 $LOCAL                                168   PIC CON REL LCL NOSHR NOEXE   RD   WRT LONG

    Total Space Allocated                 345

ENTRY POINTS

    Address   Type  Name

  0-00000000        MATSUM

VARIABLES

    Address   Type  Name           Address   Type  Name           Address   Type  Name           Address   Type  Name

  2-00000000  I*4   I          AP-00000014@ I*4   ICOLA       AP-00000010@ I*4   IROWA        2-00000004  I*4   J

ARRAYS

    Address   Type  Name                 Bytes  Dimensions

 AP-00000004@ R*8   A                      **   (*, *)
 AP-00000008@ R*8   B                      **   (*, *)
 AP-0000000C@ R*8   C                      **   (*, *)

LABELS

    Address   Label        Address   Label

      **       10            **       20
```

APPENDIX B

VELOCITY IMPARTED ON A PROJECTILE AS IT TRAVELS THROUGH A GUN TUBE

A source of additional velocity not yet analyzed in this report is the velocity imparted by angular motion as the projectile travels through the gun tube. This velocity, V_{gun}, is caused by the vehicle angular velocity continuing to impart linear velocity when all or part of the moving bullet is still in the tube.



Since the component of V_{gun} that is parallel to V_b does not totally add onto the projectile, only the component of V_{gun} normal to V_b completely adds to V_b. Call this component V_g. Hence $|V_{gun}| = \max |V_g|$. Since the stabilized gun tube does not rotate with the vehicle, the magnitude of the radius of rotation on the tube can be represented by V_{rot} defined previously in this report. Hence, given that $t_2 - t_1$ represents the elapsed time from discharge to the time the bullet completely exits the gun, we have the following equation

$$V_{gun} = \int_{t_1}^{t_2} \dot{V}_{rot}(t)dt = V_{rot}(t_2) - V_{rot}(t_1) \qquad \text{(A-1)}$$

This velocity is generally very small compared to V_{rot}, since $t_2 - t_1$ is small and so $V_{rot}(t_2) \approx V_{rot}(t_1)$. Hence, neither V_g nor V_{gun} is entered in the model.

APPENDIX C

FORMULA FOR DIFFERENTIATING A PRODUCT OF MATRICES TIMES A VECTOR

Theorem: $$\frac{d}{dt}\prod_{i=1}^{n} A_i\, R = \sum_{i=1}^{n} \left(A_1 \cdots \frac{dA_i}{dt} \cdots A_n\, R\right) + \prod_{i=1}^{n} A_i \frac{dR}{dt} \qquad \text{(B-1)}$$

Proof:

Mathematical induction is used.

(case for n = 1) Let $$AR = (a_{ij})\,(R_j) = \begin{pmatrix} \sum_{i=1}^{n} a_{ij}\, R_j \\ \vdots \\ \sum_{j=1}^{n} a_{nj}\, R_j \end{pmatrix} \qquad \text{(B-2)}$$

$$\frac{dAR}{dt} = \begin{bmatrix} \sum_{j=1}^{n} \left(\frac{da_{ij}}{dt} R_j + a_{ij} \frac{dR_j}{dt} \right) \\ \vdots \\ \sum_{j=1}^{n} \frac{da_{nj}}{dt} R_j + a_{nj} \frac{dR_i}{dt} \end{bmatrix} = \Gamma \qquad \text{(B-3)}$$

$$\left(\frac{dA}{dt}\right) R = \left(\frac{da_{ij}}{dt}\right)\left(R_j\right) = \begin{pmatrix} \sum_{j=1}^{n} \frac{da_{ij}}{dt} R_j \\ \vdots \\ \Sigma \frac{da_{nj}}{dt} R_j \end{pmatrix} \qquad \text{(B-4)}$$

$$A\frac{dR}{dt} = \begin{pmatrix} \sum_{j=1}^{n} a_{ij} \frac{dR_{ij}}{dt} \\ \vdots \\ \Sigma a_{nj} \frac{dR_j}{dt} \end{pmatrix} \qquad \text{(B-5)}$$

$$\therefore \quad \frac{dA}{dt} R + A \frac{dR}{dt} = \begin{bmatrix} \sum_{j=1}^{n} \left(\frac{da_{1j}}{dt} R_j + a_{1j} \frac{dR_j}{dt} \right) \\ \vdots \\ \sum_{j=1}^{n} \frac{da_{nj}}{dt} R_j + a_{nj} \frac{dR_j}{dt} \end{bmatrix} = \Gamma \tag{B-6}$$

$$\therefore \quad \frac{AR}{dt} = \frac{dA}{dt} R + A \frac{dR}{dt} \tag{B-7}$$

(case for n+1 matrices if true for n matrices)

Suppose

$$\frac{d}{dt} \prod_{i=1}^{n} A_i R = \sum_{i=1}^{n} \left(A_1 \ldots \frac{dA_i}{dt} \ldots A_n R \right) + \prod_{i=1}^{n} A_i \frac{dR}{dt} \tag{B-8}$$

$$\frac{d}{dt} \prod_{i=1}^{n+1} A_i R = \frac{dA_1}{dt} \left(\prod_{i=2}^{n+1} A_i \right) R + A_1 \frac{d}{dt} \left(\prod_{i=2}^{n+1} A_i R \right) \tag{B-9}$$

Without loss of generality, the subscripts can be renamed as $k \epsilon \{o, \ldots, n\}$ and then back to $i \epsilon \{1, \ldots, n+1\}$

$$\frac{d}{dt} \prod_{i=1}^{n+1} A_i R = \frac{d}{dt} A_o \prod_{k=1}^{n} A_k R = \frac{dA_o}{dt} \left(\prod_{k=1}^{n} A_k R \right) + A_o \frac{d}{dt} \prod_{k=1}^{n} A_k R \tag{B-10}$$

$$= \frac{dA_o}{dt} \left(\prod_{k=1}^{n} A_k R \right) + A_o \left[\prod_{k=1}^{n} A_k \frac{dR}{dt} + \sum_{k=1}^{n} \left(A_1 \ldots \frac{dA_k}{dt} \ldots A_n R \right) \right]$$

$$= \frac{dA_o}{dt} \left(\prod_{k=1}^{n} A_k R \right) + A_o \left[\prod_{k=1}^{n} A_k \frac{dR}{dt} \right] + \sum_{k=1}^{n} \left(A_o A_1 \ldots \frac{dA_k}{dt} \ldots A_n R \right)$$

$$= \frac{dA_1}{dt} \prod_{i=2}^{n+1} A_i R + \left(\prod_{i=1}^{n+1} A_i \frac{dR}{dt} \right) + \sum_{i=2}^{n+1} \left(A_1 A_2 \ldots \frac{dA_i}{dt} \ldots A_{n+1} R \right)$$

$$= \prod_{i=1}^{n+1} A_i \frac{dR}{dt} + \frac{dA_1}{dt} \prod_{i=2}^{n+1} A_i R + \sum_{i=2}^{n+1} \left(A_1 A_2 \ldots \frac{dA_i}{dt} \ldots A_n R \right)$$

$$= \prod_{i=1}^{n+1} A_i \frac{dR}{dt} + \sum_{i=1}^{n+1} \left(A_1 \ldots \frac{dA_i}{dt} \ldots A_{n+1} R \right) \Rightarrow \text{true for } n+1 \text{ matrices.}$$

Thus, by mathematical induction, the theorem is true.

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